Horizontal Branch Morphology and the 2nd Parameter Problem

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Abstract. We review the most outstanding issues related to the study of the morphology of the Horizontal Branch (HB) in the Color–Magnitude Diagrams of Galactic Globular Clusters and its use as *age indicator*. It is definitely demonstrated (see also Bolte, this meeting) that age cannot be *the only 2nd-P* driving the HB morphology. Other candidate *2nd-Ps* are briefly examined, with special attention to the possible influence of cluster stellar density.

A procedure is presented through which the measured HB morphology can be depurated from the effects of parameters other than age so that a rough determination of the age of globulars could still be obtained from their HBs. This method could be very useful for dating globular clusters in nearby galaxies.

1. Introduction

The Horizontal Branch (HB) stars have almost the same absolute luminosity at the same evolutionary stage, and this makes them (RR Lyrae variables) fundamental distance indicators. Moreover, as a result of large differences in the radius, HB stars present a wide color (temperature) distribution, usually called HB morphology, which is a unique astrophysical tool potentially, but whose complete understanding is still matter of continuous debate.

In general globular cluster HBs get redder as metallicity increases. Besides metallicity, [Fe/H] –the *first* parameter– the classification of HB morphologies requires however the introduction of a still unidentified *second* parameter (*2nd-P*) as perceived during the early 1960's by Sandage and Wallerstein (1960), Faulkner (1966), van den Bergh (1967), and Sandage and Wildey (1967).

2. Why does the HB morphology vary so greatly between clusters of similar composition?

This is the essence of the so-called "*2nd-P* problem" which nowadays embraces the whole subject related to studying HB morphologies. Hundreds of papers have somehow dealt with this hot subject during the last thirty years. Useful

discussions and references are reported for instance by Renzini (1977), Kraft (1979), Freeman and Norris (1981), Buonanno *et al.* (1985), Zinn (1986), Rood and Crocker (1989), Bolte (1989), VandenBerg *et al.* (1990), Sarajedini and Demarque (1990), Fusi Pecci *et al.* (1993), Buonanno (1993), Lee (1993), van den Bergh (1993), Catelan and de Freitas Pacheco (1994), Lee *et al.* (1994), Peterson *et al.* (1995).

Many candidate *2nd-Ps* have been proposed including stellar parameters and global cluster properties, and in particular: age –t–, primordial He abundance –Y_p– (but dredged-up Helium might also be important), CNO abundance –[CNO/Fe]–, rotation –ω with $\omega \uparrow \Rightarrow$ mass loss$\uparrow$–, cluster central concentration and density –ρ_0 with $\rho_0 \uparrow \Rightarrow$ mass loss $\uparrow$ (see Fig. 1). To summarize briefly the major effects, we report in Fig. 1 a few indicative plots which can be used as a sort of "tourist map" in the *2nd-P* game.

Unfortunately, models addressing the *2nd-P* require assumptions about stellar mass loss which is one of the most crucial events during the post-main-sequence evolution leading to the HB stage (Rood 1973). It is because of our too deep ignorance about mass loss and because of these assumptions that we have been less *optimistic* than others (Lee *et al.* 1990, 1994) in identifying *the 2nd-P* as age. Indeed, the physical parameter which varies from star to star leading to the differential mass loss commonly thought to cause the HB color distribution *has never been identified*. We firmly believe that the complete solution of the so-called *2nd-P* problem can hardly be achieved without identifying the parameter which leads to differential mass loss within a cluster.

3. Why is the identification of the *2nd-P* so important?

One can quote two main reasons, at least.

First, given the exceptional sensitivity of HB star location in color to almost any model parameter (Rood 1973), a complete understanding of the HB morphology yields a detailed test of the results of evolution theory of Pop II stars (Renzini and Fusi Pecci 1988).

Second, since evidence has mounted (Bolte 1989, Green ans Norris 1990, Sarajedini and Demarque 1990, VandenBerg, Bolte and Stetson 1990, Dickens *et al.* 1991, but see Catelan and de Freitas Pacheco 1994) that the *2nd-P* clusters NGC 362 and NGC 288 have strongly different HB morphologies because of an age difference, justification has grown for the use of HB morphology as a powerful *relative* age indicator.

Although the first item is surely not less important, the attention has been mostly centered on the second aspect, mainly because any route to get a "calibrated clock" is crucial to astronomy.

For instance, the overall description of the globular cluster system and early stages of Galaxy evolution proposed by the *Yale-group* (Zinn 1986, 1993, Lee *et al.* 1990, 1994, Lee 1993, Armandroff 1993) starting from the seminal work by Searle and Zinn (1978) adopts the HB morphology as "bona fide clock", and the present Galactocentric location and radial velocity, as indicators of the kinematical properties.

Once age has been justified as *the 2nd-P* , one can use this result also to show for instance that the mean age of the field HB stars decreases outward in

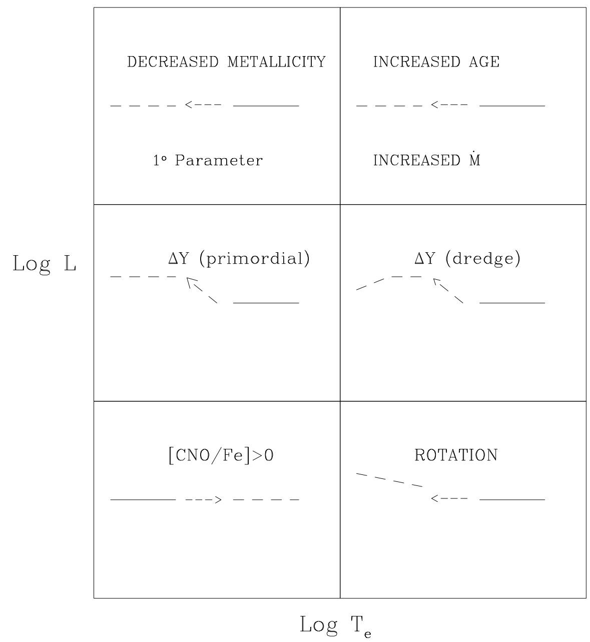

Figure 1. The *2nd-P* game: a "tourist map". Blue to the left.

the halo (Preston *et al.* 1991, Suntzeff *et al.* 1991) or to try to identify which clusters (or group of clusters) belong to a given original "fragment" (Rodgers and Paltoglou 1984, Zinn 1993, van den Bergh 1993, 1994, Majewski 1994).

4. HB morphology: a "bona fide" clock?

When one looks in details, the "HB morphology world" is indeed very complex as one finds gaps, bimodalities, blue tails, radial population gradients, etc.. Therefore, we and others (see Buonanno *et al.* 1985, Fusi Pecci *et al.* 1993, 1995 for references) have posed the question: *is age the only 2nd-P* ? If not, the definition of "young" based on the HB morphology may be misleading or, at least, it could be different from that based on the *actual measure* of the Main Sequence Turnoff (TO). This difference may well be irrelevant eventually, but we must investigate further the problem. Note that in the past few years a small set of young (from the TO) globular clusters has been detected (Pal 12, Ruprecht 106, Arp 2, Terzan 7, and IC 4499, see for references Fusi Pecci *et al.* 1995). They are peculiar in many respects and could now belong to the Milky Way as a result of capture, but can offer some useful hints in the study of the *2nd-P* problem.

5. Global versus non-global *2nd-Ps*

Following Freeman and Norris (1981), it is nowadays quite common to discuss about the so-called *global* and *non-global 2nd-Ps* . The difference between the two groups is clearly explained in the following statement from Lee (1993): "...some HBs apparently have complex structures, which seem to require a *2nd-P* internal to those peculiar clusters. I will refer to those features as the *non-global 2nd-P* phenomenon. Although they are clearly important to our understanding of the details of the HB and probably also the structure of globular clusters, they appear to have minor effect on the *global 2nd-P* phenomenon, which I define here as the mean systematic variation of HB morphology with Galactocentric distance $-R_{GC}$".

The *Yale-group* (Lee *et al.* 1994) has carefully considered the possible effects of the *2nd-Ps* proposed so far, *i.e.* t, Y_p, [CNO/Fe], ω, ρ_0 . They concluded that (1) "the variations in Y_p, [CNO/Fe], and core mass (in turn, ω) required separately to explain the *global 2nd-P* phenomenon are inconsistent with either the observed properties of the RR Lyrae variables or the observed MS-TOs in the clusters"; (2) "there is no clear evidence that the trend with R_{GC} is related to ρ_0 or absolute magnitudes of the clusters"; (3) "the variations in cluster age required to explain the trend with R_{GC} are not in conflict with any observations". Hence *age is the global 2nd-P* .

6. Are the effects of non-global *2nd-Ps* always present and important?

A typical example of the fact that there are still outstanding questions remaining is for instance the case of NGC 2808. The HB of NGC 2808 is bimodal (Ferraro *et al.* 1990), and in fact resembles a superposition (Rood *et al.* 1993) of the HBs of NGC 362 and NGC 288, the two clusters which suffer the *2nd-P* syndrome in the opposite direction and which have been adopted as "milestone" in the claim: *age is the 2nd-P* (see Lee 1993 Fig. 6 and Bolte 1993, Fig. 1 compared to Rood *et al.* 1993, Fig. 1). Since the *2nd-P* affecting the two groups of HB stars in NGC 2808 is not likely to be age (a 4-6 Gyr difference would be necessary!), one is forced to conclude that (at least in this specific case) we must consider a *third* parameter.

Moreover, the detection of peculiar features (in clusters at any R_{GC}) is becoming a rule rather than a specific exception, and the latest HST data on the distant cluster Pal 3 (see Bolte, this meeting) shows that it is "old" and with a red HB. Hence, also the subdivision itself of *global* and *non-global* quantities becomes dialectic.

Consequently, one has to split the *2nd-P* problem into two distinct parts: the first, to study which are the candidate *2nd-Ps* that mostly affect the location of the bulk of the HB star distribution; the second, to understand which are those able to alter the HB distribution, leading to bimodalities, gaps, blue tails, etc., and to determine quantitatively how important are the relative contributions to the actual observed HB morphology in each observed cluster.

For these reasons we are reluctant to believe that age, or any other single parameter, could be *the 2nd-P* . In our view, age is probably *one of the many 2nd-Ps* , possibly the most important. As suggested by Buonanno *et al.* (1985),

the definition of the *global* parameter has to be extended to mean that the parameter driving the observed HB morphology is actually the result of the "global combination" of many individual quantities and phenomena related to the formation and the chemical and dynamical evolution of each individual star in a cluster and of each cluster as a whole.

Within this framework, it is important to take into account the growing body of observational results suggesting the existence of a possible link between the dynamical history of globular clusters and the evolution of their stellar members (including blue stragglers, binaries, etc.; they *are* indeed cluster members! see for references Fusi Pecci *et al.* 1992, Bailyn 1995). In particular, Fusi Pecci *et al.* (1993, hereafter FPAL) have shown that the color extension of the HB distribution is correlated with the cluster central density $-\rho_0$, in the sense that more centrally concentrated clusters tend to have bluer HB-morphologies and often present extended blue tails. Since total luminosity and central density are correlated (Djorgovski and Meylan 1994), van den Bergh and Morris (1994) noted that the correlation found by FPAL could be a spurious effect reflecting the cluster-to-cluster variation in total luminosity.

In the following sections we report schematically the results of a study in progress (Buonanno *et al.* 1996, hereafter BAL) which support FPAL and show that the cluster density could even be a *global 2nd-P* in the sense defined by Lee (1993). Finally, we show that the simple use of HB-morphology as age indicator without taking into account other possible effects could not be appropriate, in particular for the clusters of intermediate metallicity ($-1.8 \leq [Fe/H] \leq -1.4$) where the HB morphology displays its maximum sensitivity to any variation.

7. The new HB-morphology observables and the data-base

One of the main difficulties in studying the HB consists in the difficulty to yield a satisfactory quantitative description of its detailed morphology. The *Yale-group* (Zinn 1986, Lee 1990) defined the observable $B-R/B+R+V$, where V, B, R are the number of stars located in the CMD within the instability strip, to its blue and red, respectively. This index works like a "wide-band HB-morphology photometer". It is easy to compute, but has a "low resolution" and "saturates" for very blue ($B-R/B+R+V$ =1) and very red ($B-R/B+R+V$ =-1) HBs. FPAL have shown that it is mainly sensitive to the position of the peak of the HB distribution.

To describe the blue side of the HB distribution, Preston *et al.* (1991) defined the index B_W, that is the number of HB stars in the color interval $-0.02 < (B-V)_0 < 0.18$. Later, Buonanno (1993) adopted $B2-R/B+R+V$ having defined $B2$ as the complement of B_W to B, *i.e.* $B2 = B - B_W$. While the clusters with blue HB tails saturates in the interval $0.9 < B-R/B+R+V \leq 1.0$, $B2-R/B+R+V$ spans a much larger interval. For instance, Arp 2, NGC 5897, NGC 6341 and NGC 6218 (with highly different HBs) have $B-R/B+R+V \sim 0.88$, whereas $B2-R/B+R+V$ ranks them with $-0.22, 0.09, 0.45$ and 0.77, respectively. To measure quantitatively the blue tails we also defined $B2/B+R+V$, *i.e.* the *normalized* number of stars located in the HB blue tail (to overcome the the point raised to FPAL by van den Bergh and Morris 1994).

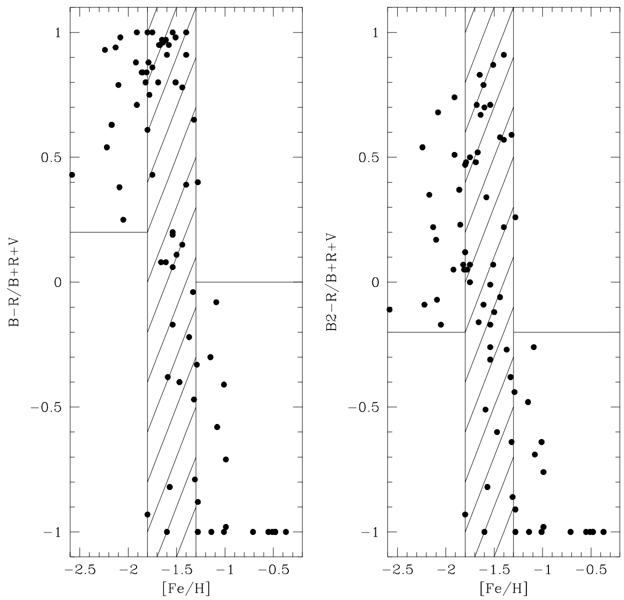

Figure 2. Observables describing the HB morphology *vs.* metallicity. Note the large variation of the HB morphology in the intermediate-metallicity regime (shaded area)

Our complete database collects data for 69 halo globular clusters for which we have obtained the above HB-morphology observables from the available photometries. $[Fe/H]$, $log\rho_0$ and R_{GC} are taken from Djorgovski (1993). The de-reddened colors of the peak of the HB-distributions $-(B-V)_{peak}-$ are drawn from FPAL or newly computed. The "relative" ages based on TO-properties for 27 clusters are taken from BAL, as well as the whole estimate and treatment of the errors. Note that the use of other data-sources and the ages recently presented by Chaboyer *et al.* (1995) do not modify the essence of these results (see BAL for a discussion).

As shown by FPAL (Fig. 1), the sensitivity of the location in temperature (color) of the HB stars is dependent on metallicity in a strongly non-linear way. Therefore, we selected from the plots shown in Fig. 2 the region of maximum sensitivity, $-1.8 \leq [Fe/H] \leq -1.4$, and present here just the results for this intermediate-metallicity window.

8. Correlations between $B2/B+R+V$ and $log\rho_0$ and R_{GC}

In order to check the possible connection between $log\rho_0$ and HB morphology claimed by FPAL, we divided the sample in two groups with: (i) $log\rho_0 > 3$ (39 objects) and (ii) $log\rho_0 \leq 3$ (26 objects). As shown in Fig. 3, the two cumulative distributions with respect to $B2/B+R+V$ are strongly different, whereas they are indistinguishable with respect to [Fe/H]. A KS-test yield a probability

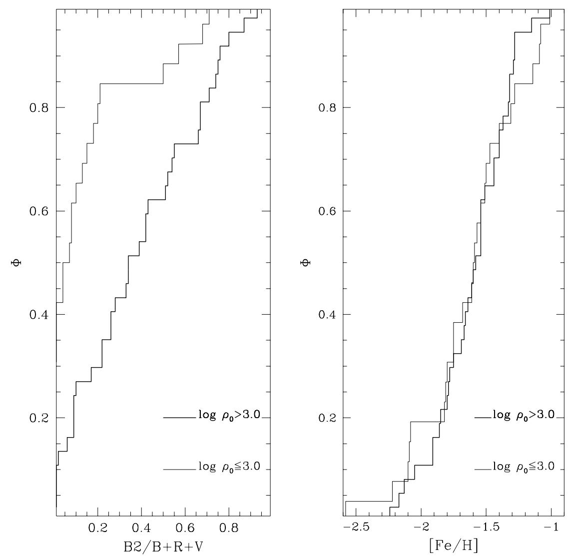

Figure 3. Cumulative distributions in $B2-R/B+R+V$ (left panel) and in $[Fe/H]$ (right panel) for clusters of different central densities

of only 0.02% that the two groups are extracted from the same population in $B2/B+R+V$. Hence, if $\rho_0 \uparrow \quad \Rightarrow$ HB morphology gets bluer.

Due to shortage of space, a complete quantitative analysis and demonstration on how cluster stellar density may play a rôle in influencing the HB morhology can be found in FPAL and in the the forthcoming paper (BAL). However, once demonstrated the existence of this significant influence, at least for intermediate-metallicity clusters (where HB sensitivity is maximum), and considering that nearly half of the halo clusters are of intermediate metallicity, it would be quite evident that using HB-morphology as age indicator without taking into account the possible effects due to the differences in the cluster central density may produce very noisy, if not misleading, age scales even if age were the *dominant 2nd-P* .

In particular, looking at the mean systematic variation of HB morphology with R_{GC} (the *global 2nd-P* effect), it can be argued that this phenomenon could be partially due to the well known anti-correlation existing between $log\rho_0$ and R_{GC} coupled with the tendency of loose clusters to display redder HB morphologies (at fixed metallicity) as claimed above.

9. Playing with HB morphologies and ages

Having at disposal a set of independent *relative* cluster ages, one can play with the data to verify whether, under the assumption that age is *not* the only *2nd-P* , a proper combination of the effects due to age and, for instance, to differences in ρ_0 can offer a more stringent correlation with the observable adopted to describe the HB morphology.

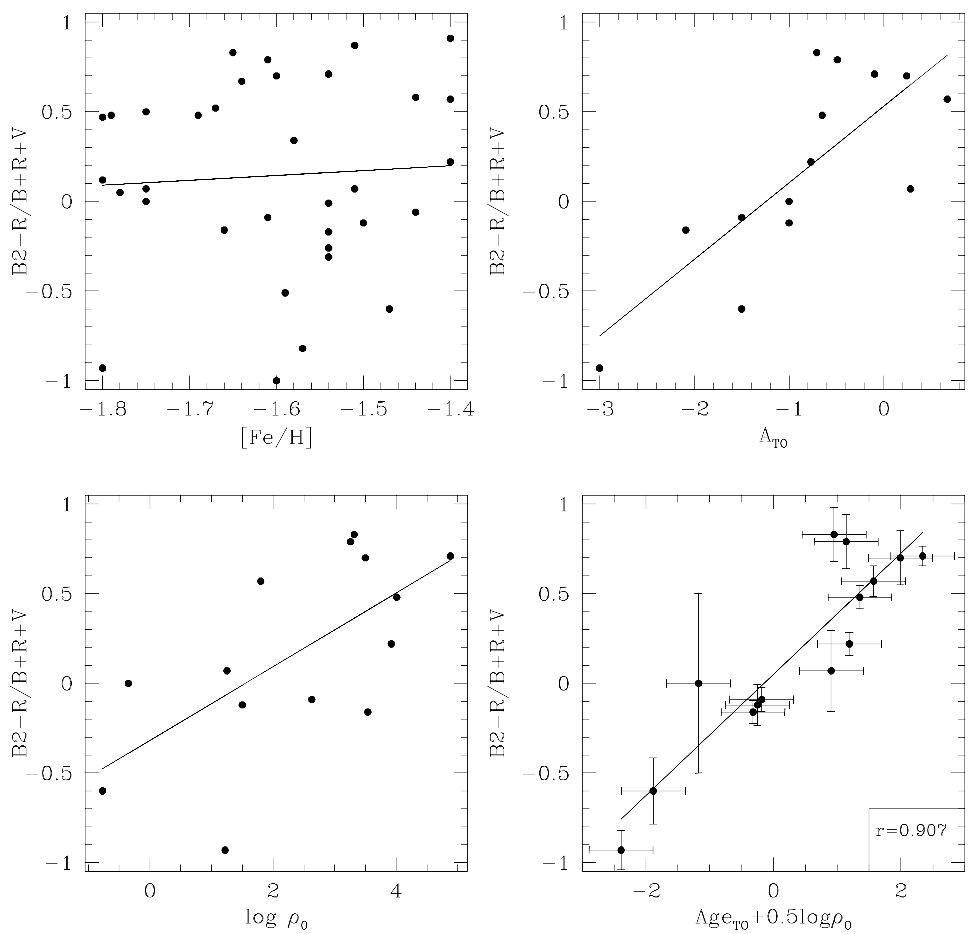

Figure 4. The dependence of $B2-R/B+R+V$ on $[Fe/H]$, A_{TO} and $log\rho_0$ for the clusters with $-1.4 \leq [Fe/H] \leq -1.8$. In the bottom-left panel the bivariate correlation is shown.

Due to the poorness of the sample and the still high uncertainties on the relative ages (here expressed as differences with respect to an arbitrary zero-point adopted as reference by BAL), the results presented in Fig. 4 are essentially indicative. However, we find a curious indication, at least.

In synthesis, Fig. 4a shows the distribution of the clusters having $-1.8 \leq [Fe/H] \leq -1.4$ in the plane $B2-R/B+R+V$ *vs.* [Fe/H]. As can be seen, within this metallicity interval, where the sensitivity of the HB morphology to the variation of any parameter is highest, there is no correlation with [Fe/H] –the *first* parameter. Panel *b* shows that, for the few clusters for which TO-ages are available, there is a quite evident correlation with $B2-R/B+R+V$. In addition, panel *c)* shows that a (slightly weaker) correlation can be found for the same clusters also between $B2-R/B+R+V$ and $log\rho_0$. Finally, panel *d* leads to the most interesting evidence that, if the effects of the two possible dependences of the HB morphology are combined via a bivariate analysis (*i.e.* by seeking for the best linear combination of Age_{TO} and $log\rho_0$ which optimizes the ranking of the $B2-R/B+R+V$ values), one obtains a significant improvement of the correlation with respect to the monovariate cases (panels *b,c*). The linear correlation coefficient yields a probabiblity less than 0.05% that the two vectors in panel *d* are actually uncorrelated.

Based on this exercise, which of course requires a much deeper analysis and confirmation, one might conclude that the manifold of HB morphologies at fixed metallicity is at least *two-dimensional.* In the overall scenario of the classification of the HB morphology of Galactic GC's, this would imply that while metallicity is *the first* parameter, *the 2nd-P* is probably a complex combination of the effects due to various *2nd-Ps* , or, if one wants to keep the major rôle associated to age, that a complete understanding of the HB morphology requires the considerations of a *third* parameter, at least.

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